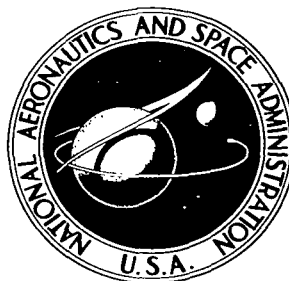


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EVAPORATION RATES FOR VARIOUS  
ORGANIC LIQUID AND SOLID LUBRICANTS  
IN VACUUM TO  $10^{-8}$  MILLIMETER OF  
MERCURY AT  $55^{\circ}$  TO  $1100^{\circ}$  F

*by Donald H. Buckley and Robert L. Johnson*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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AT 55° TO 1100° F

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SUMMARY

The evaporation rates for various organic lubricants were measured in vacuum ( $10^{-6}$  to  $10^{-8}$  mm Hg) and at ambient temperature to 1100° F. These materials included liquids, greases, and solids.

The evaporation rate measurements were made with a vacuum bell-jar evaporation system employing an electronic balance to measure weight changes to one-hundredth of a milligram. The specimens were heated by a wire-wound furnace, and evaporated material was condensed on a liquid-nitrogen-cooled condenser plate. The weight change of the specimen was continuously recorded on a strip chart recorder.

Some of the lubricants examined were polyphenyl ethers, polyalkylene glycols, silicones, fluorocarbon polymers, polytetrafluoroethylene, polychlorotrifluoroethylene, and phthalocyanines. Differences in molecular weight were found to influence markedly the evaporation rates of lubricants. With a polyalkylene glycol fluid having a molecular weight of 13,500, the evaporation rate was approximately  $10^{-6}$  g/sq cm/sec at 550° F. This same evaporation rate was achieved with a 660-molecular-weight fluid at a temperature of 55° F. The results obtained with a series of polyalkylene glycol fluids of different composition but having equivalent molecular weights (1000) indicated that the evaporation rate of the series over a range of temperatures could be represented by a single curve. The solids polytetrafluoroethylene, polychlorotrifluoroethylene, and fluorocarbon polymers were also found to exhibit evaporation rates with a molecular weight dependence. For one of the polyphenyl ethers, good agreement was found with data in the literature.

INTRODUCTION

The operation of mechanical systems in the vacuum environment of space presents special lubrication problems. For long-period operation of mechanical components that require lubrication, conventional oil and grease lubricants may prove inadequate because of their high evaporation rates (ref. 1). In many of these applications, solid films (e.g., molybdenum disulfide) may be successfully utilized in replacing the more conventional lubricants. There are, however, situations in which an oil- or grease-type structure can be used most effectively.

For example, in a fully or partially sealed system, liquids or greases may serve satisfactorily (ref. 2).

A number of oils and greases have physical properties (e.g., low vapor pressures) that make them desirable candidates for certain vacuum applications. Although many of these materials have been primarily developed for high temperatures or a radiation environment, they may also find usefulness in the vacuum of space. Some of the silicone derivatives and polyphenyl ethers are of interest. A chlorinated polysiloxane has been successfully used in vacuum bearing experiments, and, because of their low vapor pressure, two polyphenyl ethers are being used as diffusion pump fluids in the ultrahigh vacuum range (refs. 3 and 4).

From the Langmuir equation for vapor pressure determinations, a relation between molecular weight and evaporation rate for materials is known to exist. The use of these relations with some lubricants and self-lubricating materials, however, becomes difficult because many of these materials (e.g., polymers) have a range of molecular weights, and the quoted molecular weights are frequently averages. In addition, there are other factors that do not enter this equation, such as molecular dissociation or structural degradation. The vapor pressure for lubricants is determined, in many instances, over a narrow range of temperatures, and the data are then extrapolated to other temperatures. Such extrapolation can be misleading if a lubricant (grease) is a mixture of two or more molecular weight species, each having its own characteristic evaporation rate. The evaporation rate of such a material may not be represented by a single line of constant slope for a range of temperatures.

The objectives of this investigation were to determine in vacuum ( $10^{-6}$  to  $10^{-8}$  mm Hg) at temperatures from  $55^{\circ}$  F to the limiting temperature of the material: (1) the evaporation rates for various liquids (polyalkylene glycols, polyphenyl ethers, fluorinated polymers, and silicone fluids); (2) the influence of molecular weight on the evaporation rates for some polyalkylene glycols and fluorocarbon telomers; and (3) the evaporation rates of other organic materials that offer promise as lubricants in a vacuum environment.

Samples weighing approximately 100 milligrams were evaporated from a 5/16-inch-diameter pan in a vacuum bell jar at temperatures to  $1100^{\circ}$  F. An electronic balance was used for continuous recording of weight with time at a particular temperature.

## THEORETICAL CONSIDERATIONS FOR SPACE SIMULATION

### IN EVAPORATION STUDIES

In a consideration of the evaporation of lubricants in space, a number of factors can play an important role in operating mechanical systems. The evaporation of a lubricant will depend to a large extent on the area of use. If, for example, the lubricant is used within a system that is designed with geometric obstructions to the escape of lubricant molecules, the rate of lubricant evaporation will depend on the nature and type of these condenser surfaces. Under such conditions, when considerable restriction to evaporation is afforded as a result of system design, the lubricant loss may be very low. If, however, the lubricant

is present on a surface that is completely exposed to the environment of space, where the lubricant "sees" nothing but space, the rate of lubricant loss will be much higher. Since, in most space lubrication applications, design geometry can be expected to inhibit evaporation to some degree, the case of the lubricant being completely exposed to space represents the extreme. If, however, the behavior of these materials in space is to be understood, the basic evaporation studies herein must be designed to represent the extreme condition.

The evaporation apparatus used in this investigation was designed to represent this extreme case. The specimen surface is completely exposed to the vacuum environment with no geometric restrictions to the evaporating species. A cryogenically cooled condensing surface is placed very close to the specimen to condense evaporated material and prevent an equilibrium condition from existing above the specimen surface. Equilibrium would represent a balance between the rate of evaporation and the rate of recondensation on the parent surface. To simulate the conditions experienced in space, the system must be driven as completely as possible in the direction of total loss of evaporated material. The lower the temperature of this condensing surface, the greater will be the sticking probability of condensing molecules, and the lower will be the evaporation rate from the condenser surface.

In a space environment an extreme of temperatures may be encountered (hot to cold). Those mechanisms that "see" the space environment directly may experience extremely low temperatures. There are, however, components that "see" extremely high temperatures, such as space radiators. The temperature range of this investigation was from 55° to 1100° F.

In order to establish some acceptable reference value for evaporation rates, a calculation was made for a conventional diester lubricant (MIL-L-7808). If the diester were raised to a temperature in vacuum to which it would exhibit an evaporation rate of  $10^{-7}$  g/sq cm/sec, it would take approximately 36 seconds to completely evaporate a film of this fluid 400 angstroms thick. An evaporation rate of  $10^{-7}$  g/sq cm/sec has been arbitrarily established as representing a threshold evaporation rate. It must be indicated, however, that this value represents unrestricted evaporation. Any restrictions could appreciably reduce this value. In the Tiros II satellite, for example, a diester was used. It was impregnated in a porous sintered nylon with molecular flow seals in the system and operated successfully for over 1 year. Also with shields, rolling-element bearings have operated to prolonged periods in vacuum with silicone oil.

#### EVAPORATION AND VAPOR PRESSURE EQUATIONS

It is well known that molecules are perpetually evaporating from liquids and solids. The number will vary from material to material. A means for calculating this number can be derived or expressed by the use of the Langmuir equation, which was derived from Knudsen and founded on the Maxwell-Boltzmann law (refs. 5 and 6),

$$G = \frac{PS}{\sqrt{2\pi MRT}}$$

where

G evaporation rate, g/sq cm/sec

P vapor pressure, mm Hg

S area, sq cm

M molecular weight

R gas constant

T temperature, °K

Langmuir determined the vapor pressure of tungsten from its evaporation rate in accordance with the following equation (ref. 7). Other investigators have shown this equation applies to pure materials of many types (ref. 8):

$$P = 17.14 G \sqrt{\frac{T}{M}}$$

Hickman, in his studies of high-vacuum distillation of oils, solved for evaporation rate using the Langmuir equation (ref. 9):

$$G = 5.833 \times 10^{-2} P \sqrt{\frac{M}{T}}$$

If the vapor pressure of a material is known at one temperature  $T_1$  and its value is desired for some other temperature  $T_2$ , it can be calculated with heats of vaporization and sublimation by means of the Clausius-Clapeyron equations in their integrated forms:

$$\log \frac{P_2}{P_1} = \frac{\Delta H_v}{2.303R} \frac{T_2 - T_1}{T_1 T_2}$$

$$\log \frac{P_2}{P_1} = \frac{\Delta H_s}{2.303R} \frac{T_2 - T_1}{T_1 T_2}$$

where

$\Delta H_v$  heat of vaporization

$\Delta H_s$  heat of sublimation

From the preceding equations, it is obvious that one of the parameters can be determined if the others are known.

With a knowledge of heats of vaporization or sublimation and a single vapor pressure, the vapor pressure at other temperatures may be calculated. The vapor pressure for materials has been determined experimentally by means of such devices as the isoteniscope and the Knudsen cell described and discussed in the appendix.

## ENVIRONMENTAL PRESSURES

The ambient pressure of the environment can markedly influence the rate of evaporation of materials. With high environmental pressures, many collisions can occur between evaporating molecules from a specimen and those of the environmental gas. Some of the evaporating species can thereby be driven back to the parent specimen surface.

Hickman has pointed out that the presence of the atmospheric molecules keeps water and other materials like propyl phthalate from gasifying rapidly at room temperature. The effects of ambient pressure on evaporation rate can readily be seen for tungsten in figure 1, which was obtained from reference 10. Decreasing the ambient pressure, at a constant temperature (2870° K), 1000-fold increased the evaporation rate by a factor of 100. Data for the evaporation rate of  $C_6H_4COO(C_8H_{17})_2$  as a function of ambient pressure are also presented in figure 1 (ref. 9). Here, decreasing pressures from  $2 \times 10^{-2}$  to  $2 \times 10^{-4}$  increased the evaporation rate by a factor of 10. These results indicate the necessity of specifying ambient pressures.

If the ambient pressure of a gas in a chamber is reduced from the viscous flow region to that of molecular flow and if the distance between the specimen and the condensing surface is short, the evaporated material can be made to condense without undergoing collisions with other gas molecules. This will occur if the mean free path (distance an evaporated molecule travels before undergoing a collision with other gas molecules) is large compared with the distance between the specimen and the condenser. The data of the following table, obtained from reference 9, give some indication of the probability of collision for a mercury molecule in a residual gas environment at a pressure of  $10^{-3}$  millimeter of mercury with various evaporation to condensation distances:

Distance between evaporator and condenser, cm	Multiples of mean free path	Probability of molecule making journey without collision, percent
1	0.25	77.5
2	.50	60.1
20	5.0	.005

## ADSORBATES

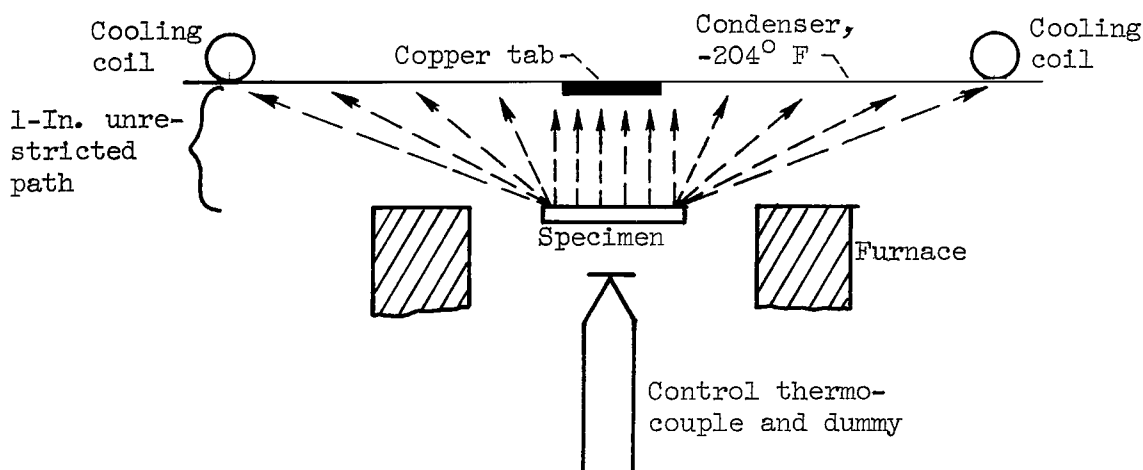
Another problem in evaporation studies of lubricants is that associated with the presence of gases and/or water in the lubricant. A considerable portion of these gases is removed on pump down for those studies conducted in vacuum. Even in vacuum, however, some heating is required to outgas the materials thoroughly before evaporation measurements can be reliably made.

## DEGRADATION

In evaporation studies with large molecules such as with oils and polymers, consideration must be given to the thermal degradation of these materials at high temperatures in vacuum, since thermal degradation contributes to the measured weight loss. As the temperature is increased, the influence of degradation effects becomes more pronounced. Further, with polymers, the presence of contaminants may influence such degradation. A single oxygen molecule, metal ion, or free radical might be sufficient to initiate a decomposition mechanism.

## APPARATUS

The apparatus used in this investigation is described in detail in reference 1 and is shown schematically in figure 2 and sketch (a). The basic component of the apparatus consisted of the specimen, 100 milligrams (approx.) of the material under investigation, which was contained in a 5/16-inch-diameter platinum pan. The pan was suspended by means of a stirrup and a wire from an electronic balance. The electronic balance was capable of measuring weight changes of one-hundredth of a milligram. During an experiment, weight changes were continuously recorded on a strip chart recorder. Data were recorded after reaching a stable evaporation rate. The sample was suspended at the upper end of a tungsten-wire-wound cylindrical furnace. A dummy thermocouple was positioned on the axis of the furnace just below the specimen pan for specimen temperature control and the system calibrated. About 1 inch above the furnace was a copper condensing shield. The shield was cooled with liquid nitrogen, and the temperature at the center of the shield above the specimen was  $-204^{\circ}\text{F}$  or colder during an experiment. On the side of the shield facing the specimen was a copper tab for X-ray analysis of condensate composition.



(a)

Pressure within the bell jar was measured near the furnace with a nude hot cathode ionization gage. Pressures of  $10^{-8}$  to  $10^{-7}$  millimeter of mercury were



normally used as starting ambient pressures. As samples are heated, however, and evaporation begins, the pressure rises. The ultimate pressure reached will be influenced by the temperature and the specimen.

The pumping system was a conventional bell-jar system with a mechanical pump and a 4-inch oil diffusion pump with a water-cooled optical baffle.

## RESULTS AND DISCUSSION

The polyphenyl ethers have been given considerable consideration in recent years as pumping fluids for vacuum systems and lubricants for high temperature and radiation environments. The consideration of these materials for such applications is based on the molecular stability and relatively inert characteristics of these materials. Further, the low vapor pressures of these materials have made them attractive as diffusion pump fluids. In order to determine the ability of these materials to be retained as lubricants on surfaces in vacuum, some evaporation experiments were conducted with three fluids: a four-ring polyphenyl ether, a five-ring isomeric polyphenyl ether, and a six-ring polyphenyl ether. The results obtained are presented in figure 3. The four-ring polyphenyl ether has a molecular weight of 354, the five-ring ether 447, and the six-ring ether 539. A marked difference in evaporation was noted for the three ethers. In comparing the four- and six-ring ethers, the results show that the higher molecular weight fluid had the lower evaporation rate. In order to obtain a comparison of the evaporation of the ether with data obtained by other investigators, the evaporation rate of the five-ring polyphenyl ether is compared with two other sources (refs. 4 and 11) in figure 4. The data obtained from these sources were at temperatures of 480° F and above, while the data obtained in this investigation were at lower temperatures. If the curve obtained for the data of the present investigation shown in figure 3 is extrapolated to the higher temperatures, such extrapolation (fig. 4) reasonably compares with the reference data.

The polyalkylene glycol fluids can be obtained in a range of viscosities and molecular weights. These fluids were also studied in vacuum evaporation rate experiments. A series of polyalkylene glycol fluids of approximately the same molecular weight (1000) were examined. The results obtained in these studies are presented in figure 5, and the chemical names and structural formulas are presented in table I. The evaporation data for all five materials examined fit a single curve, which indicates that molecular weight primarily influenced evaporation rate despite the differences in physical properties of the fluids.

Since the molecular weights of conventional lubricating fluids may vary, some evaporation experiments were conducted with various molecular weight fractions of the water-soluble polyalkylene glycols to determine the influence of molecular weight. The results obtained in these experiments are presented in figure 6. With a 13,500-molecular-weight polyalkylene glycol very little change in the slope for evaporation rate was observed at ambient temperatures to 450° F. Above 450° F the evaporation rate began to increase more markedly. As the molecular weight of the fluid decreased, a marked increase in evaporation rate was noted even at low temperatures. With the 660-molecular-weight fluid, evaporation was very rapid even at 55° F. The evaporation rate for the 660-molecular-weight

fluid was measured at 55° F for various ambient pressures, as indicated in figure 6. At a pressure of  $10^{-7}$  millimeter of mercury and 100° F, the evaporation rate of the glycol became extremely high. These results indicate that molecular weight should be a consideration in the selection of candidate lubricants for space applications.

The relatively low vapor pressure for the silicone fluids has resulted in a number of investigators examining these fluids for vacuum lubrication applications. The most frequently considered fluid is the methyl chlorophenyl silicone. This fluid has a molecular weight range of 800 to 6000. To obtain some idea of the evaporation rate of this material in vacuum, evaporation rate measurements were made in vacuum to 550° F. (The temperature was kept below 600° F because, above this temperature, molecular rearrangement occurs and results in volatile short chain molecules.) The results obtained in these experiments are presented in figure 7. Also presented in figure 7 is the evaporation rate at various temperatures for a silicone grease, which is methyl chlorophenyl silicone base fluid containing a lithium soap thickener. The evaporation rate very closely approximates that of the oil; this might be anticipated since the base fluid is the same oil. If sufficient time were allotted for complete evaporation of the base fluid, the evaporation rate could be expected to change.

The evaporation rates for three greases were determined in vacuum at temperatures to 300° F. The results obtained are presented in figure 8. Although these particular greases were not formulated for vacuum applications, they possess in their composition what should be relatively stable constituents. One grease contains a polyphenyl ether base fluid, while another has a silicone fluid. The thickener, a red pigment material, was the same for both base fluids. The third grease was a polyalkylated aromatic fluid with a calcium acetate complex thickener. At temperatures above 250° F, the polyphenyl ether base grease showed the lowest evaporation rate.

The evaporation rates of two low-molecular-weight (2000 and 3700) fluorocarbon telomers were determined in vacuum because these materials appear to have good lubricating properties. The results obtained in these experiments are presented in figure 9. A single curve could be drawn for the evaporation rate of the two telomers to 450° F. At 550° F the evaporation rate of the higher molecular weight material (3700) was lower than that of the lower molecular weight material. It appears that the molecular weight difference is not great enough to produce any marked differences in the evaporation rate of the two materials at temperatures to 450° F. At temperatures above 450° F the difference becomes pronounced.

Polytetrafluoroethylene has been used in many lubrication applications, which have encompassed a wide variety of environments. Recently, these environments have included vacuum (ref. 2). The evaporation rate of unfilled polytetrafluoroethylene obtained from the manufacturer some years ago was measured and reported in reference 1. In order to determine the effect of differences (such as molecular weight and contamination) in various production lots of this material, evaporation rate measurements were made for three other unfilled polytetrafluoroethylene compositions, and the results obtained are presented in figure 10 (temperature scale changed from that of previous figures). With the polytetrafluoroethylene composition from reference 1, a marked change in weight was

observed at temperatures above 500° F. This change may be associated with the thermal degradation of the polymer. With the unfilled extruded polymer this marked rapid weight loss was not observed until a temperature of 950° F was reached. The presence of contaminants such as oxygen, free radicals, and/or metal ions could markedly influence the decomposition temperature for the various compositions. The presence, for example, of oxygen has been shown to influence the radiation stability of polytetrafluoroethylene and could exhibit a similar influence in evaporation studies. The thermal stability limit for PTFE in air (O<sub>2</sub>) has been associated with a temperature of 550° F. In the absence of oxygen (vacuum), however, it appears the material is stable to much higher temperatures.

The rates measured in these experiments with the extruded composition were checked by cooling the sample and repeating the procedure with the same sample. The rates measured agreed with those measured initially. The molded PTFE compositions (1 and 6) both exhibited relatively low rates of evaporation at temperatures to 800° F. Above 800° F the rate began to increase for both, more rapidly, however, for the PTFE 1 than for the PTFE 6. PTFE 6 has a higher molecular weight than PTFE 1, which exhibits the lower evaporation rate at higher temperatures, as would be expected. The variation in results obtained for the PTFE compositions indicates that care must be exercised in the characterization and selection of the proper PTFE composition for vacuum lubrication applications, since the differences observed in this investigation may have resulted from differences in molecular weight distribution and in contaminants within the various materials.

The evaporation rates for some polychlorotrifluoroethylene samples of known molecular weights were determined in vacuum at ambient temperatures to 600° F, and the results obtained are presented in figure 11. The molecular weights for the homopolymer of polychlorotrifluoroethylene were 76,000, 157,000, 185,000, and 196,000. The evaporation rate for a copolymer of chlorotrifluoroethylene and vinylidene fluoride was also measured. The 76,000-molecular-weight polymer exhibited a higher evaporation rate than the samples of higher molecular weight. At 550° F, the rate became sufficiently high and could not be accurately measured. With the heavier materials of the homopolymer, no significant difference in evaporation rates could be noted. This may have resulted from the relatively small differences in molecular weight. Decomposition did not appear to occur with these materials until a temperature of 600° F was reached.

The phthalocyanines (both metal free and copper) have been considered as high-temperature lubricants (ref. 12). Some consideration has been given to the possible use of these materials as lubricants in a vacuum environment even though their lubricating properties have not been demonstrated. Evaporation rate measurements were therefore made on metal-free and copper phthalocyanine. The results obtained are presented in figure 12. In general, the evaporation rate of both materials was low in vacuum to 800° or 850° F. The change in evaporation rate was less than half an order of magnitude from 55° to 850° F. It has been indicated, however, that, at 950° F, phthalocyanine will sublime without decomposition (ref. 12).

#### SUMMARY OF RESULTS

From the results obtained in evaporation rate experiments in this investiga-

tion, the following summary remarks can be made:

1. With a series of polyalkylene glycol fluids of varied composition but having approximately the same molecular weight (1000), the evaporation rate for five fluids, at temperatures from 50° to 450° F, could be represented by a single evaporation rate curve. The evaporation rate for these materials was relatively high at temperatures above 450° F.

2. Varying the molecular weight of polyalkylene glycol fluids markedly influenced evaporation rates for these fluids in vacuum. With a fluid having a molecular weight of 13,500, the evaporation rate did not markedly change from 55° to 450° F, while a 660-molecular-weight fluid exhibited a relatively high rate of evaporation even at 55° F.

3. The evaporation rate for two fluorocarbon polymer compositions of different molecular weight (2000 and 3700) could be represented by a single curve from 55° to 450° F. This is believed to result from the relatively small differences in molecular weight, which did not permit detection in evaporation rate measurements made within the sensitivity of the equipment used in this investigation. Above 450° F the evaporation rates for these materials were relatively high.

4. With polytetrafluoroethylene, different compositions exhibited marked differences in the rate of weight change with temperature. These differences may have resulted from differences in molecular weight distribution and/or contaminants within the various materials examined in this investigation.

5. Both the methyl chlorophenyl silicone oil and the grease containing it as a base fluid exhibited the same rate of evaporation to 550° F. If sufficient time had been allowed in the grease studies from complete evaporation of the oil, this rate would most probably have changed.

6. Although the phthalocyanines have not been shown to have good lubricating characteristics in vacuum, the relatively low evaporation rates exhibited by these materials at ambient temperatures to 850° F indicate they may at least have potential as grease fillers.

7. The evaporation data obtained in this investigation with the polyphenyl ethers correlate very well with those calculated from vapor pressures obtained from other sources.

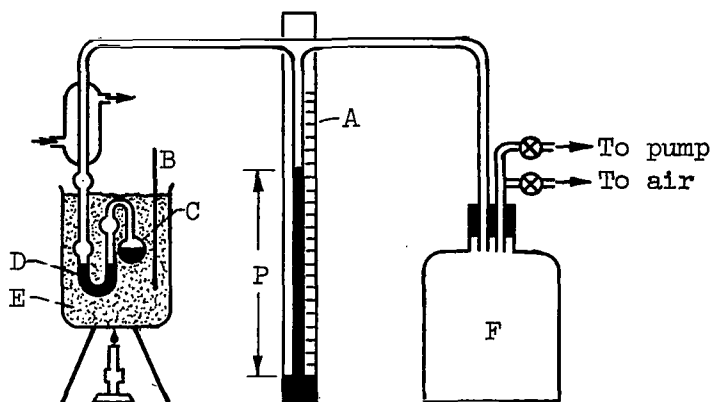
Lewis Research Center

National Aeronautics and Space Administration  
Cleveland, Ohio, August 23, 1963

## APPENDIX - DEVICES FOR MEASURING VAPOR PRESSURE

### Isoteniscope

The isoteniscope is a simple apparatus for the determination of vapor pressures of substances over a range of temperature (see sketch (b)).



(b)

The bulb of the isoteniscope C is filled one-half to three-fourths full of the liquid under investigation, and the U-shaped portion of the tube D is filled 2 to 3 centimeters high with the liquid. When the bulb is filled, the liquid levels must do the same in the U-tube. The U-tube is then attached to the rest of the apparatus and surrounded by a bath E, the temperature of which is measured by thermocouple B; A is the portion of the apparatus for measuring pressure; and F is a bottle for smoothing out pressure variations in the system. The bottle can be connected alternately to a vacuum pump or air. Operation of the apparatus involves evacuating the system until the liquid boils vigorously at C to expel all air from C and D. The bath E is then heated to the desired temperature, and air is slowly admitted to the system until the liquid levels in the U-tube D are exactly equal. Under these conditions the pressure on the two sides of the tube must be equal. Then, the vapor pressure in C must be the same as the pressure in the rest of the apparatus and can be obtained from reading the pressure of the mercury column at A. The difference between the barometric pressure and that at A is the vapor pressure of the liquid in C at the temperature of the bath. By changing the temperature of the bath, vapor pressures may be obtained at various temperatures. Prior to vapor-pressure determinations with the isoteniscope, it is desirable to vacuum degas the fluids to reduce possible error introduced into the vapor-pressure determinations by dissolved gases.

### Knudsen Cell

The Knudsen cell used in the determination of vapor pressures measures effusion rates of gases through a small orifice. Knudsen, in his studies, used a thin platinum strip 0.0025 millimeter thick with a 0.025-millimeter orifice (ref. 6). However, this cell is applicable only under those conditions in which the diameter of the orifice is one-tenth or less the mean free path of the gas

molecules at the pressure of effusion.

One difficulty encountered with the Knudsen cell is the resistance offered to effusing gases. A gas streaming through a narrow orifice experiences a resistance to flow, so the velocity of this flow decreases uniformly from the center outward to the edge of the orifice. Therefore, a correction factor has been introduced for this effect. A number of investigators have termed this correction factor the "K factor or resistance factor." It may be defined as representing the ratio between the rate at which gas leaves the outlet of the orifice and that at which gas strikes the inlet. These K factors have been measured for various orifices, and the values are available in the literature (ref. 9).

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TABLE I. - STRUCTURAL FORMULAS FOR POLYALKYLENE GLYCOLS

Chemical name	Structural formulas
Polyethylene glycol	$\text{HO}-(\text{CH}_2-\underset{\text{H}}{\text{CH}}-\text{O})_n-\text{H}$
Polypropylene glycol	$\text{HO}-(\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-\text{O})_n-\text{H}$
Monoethyl-monobutyl diether of polypropyl oxide	$\text{C}_4\text{H}_9-\text{O}-(\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-\text{O})_n-\text{C}_2\text{H}_5$
Monobutyl ether of polypropyl oxide	$\text{C}_4\text{H}_9-\text{O}-\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-\text{O}-\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-\text{O}-(\text{CH}_2-\underset{\text{CH}_3}{\text{CH}}-\text{O})_n-\text{H}$
Monobutyl ether of a random copolymer of 50 percent ethylene and 50 percent propylene oxide	
Random copolymer of 75 percent ethylene oxide and 25 percent propylene oxide	



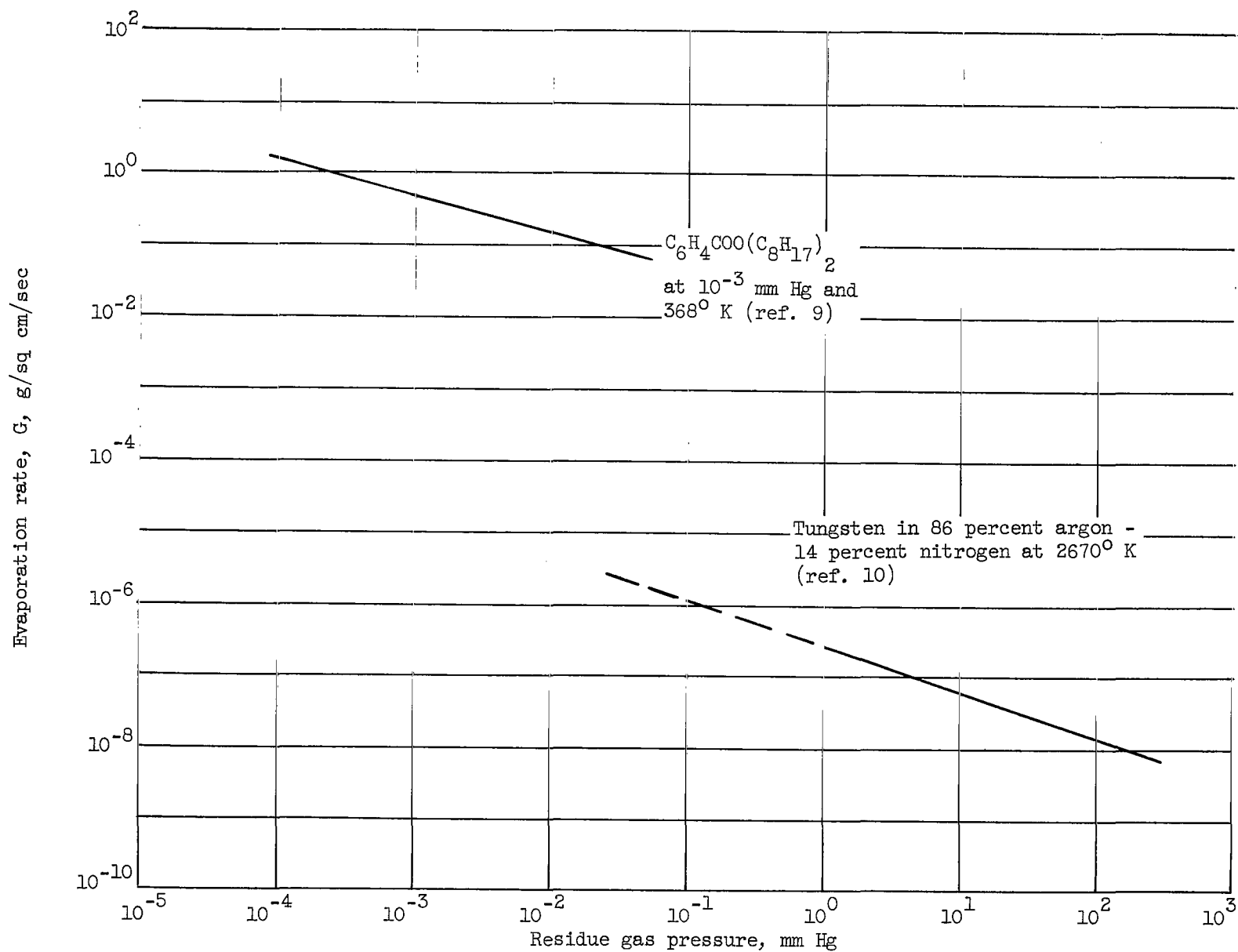


Figure 1. - Evaporation rates of  $C_6H_4COO(C_8H_{17})_2$  and tungsten at various ambient temperatures and pressures.

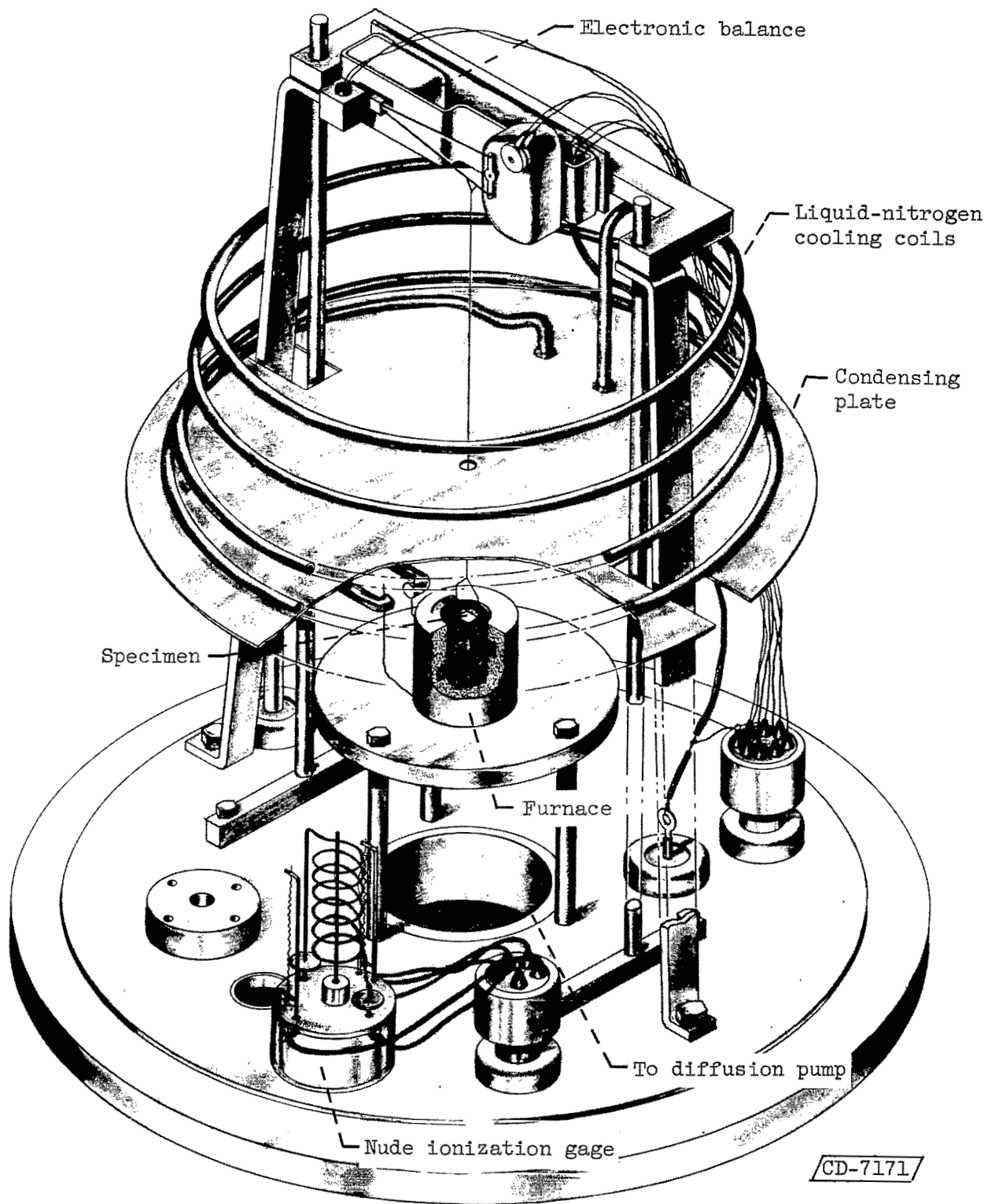


Figure 2. - Vacuum evaporation apparatus.

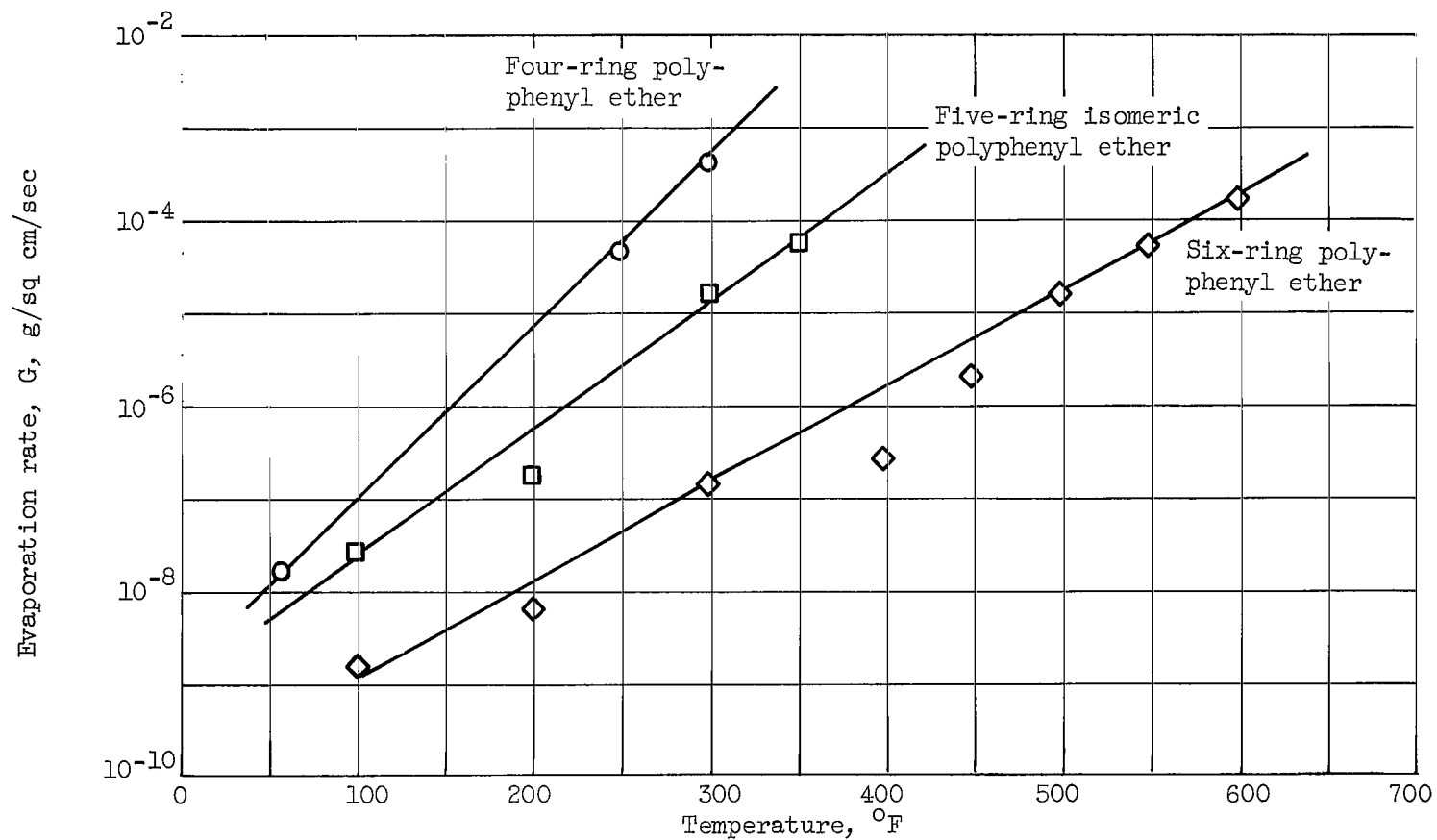


Figure 3. - Evaporation rates for three polyphenyl ethers in vacuum ( $10^{-7}$  mm Hg).

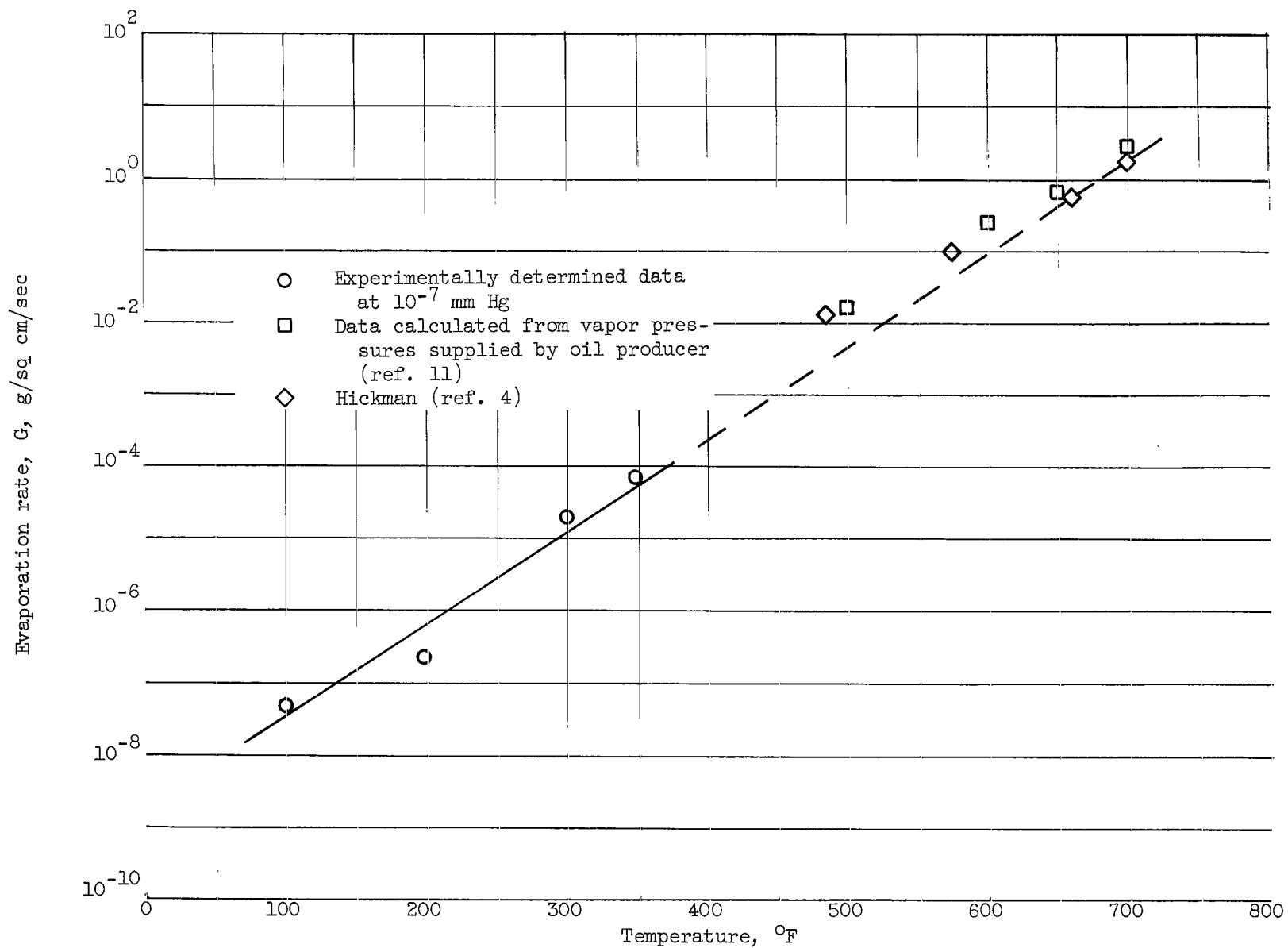


Figure 4. - Evaporation rate for isomeric five-ring polyphenyl ether in vacuum ( $10^{-7}$  mm Hg).

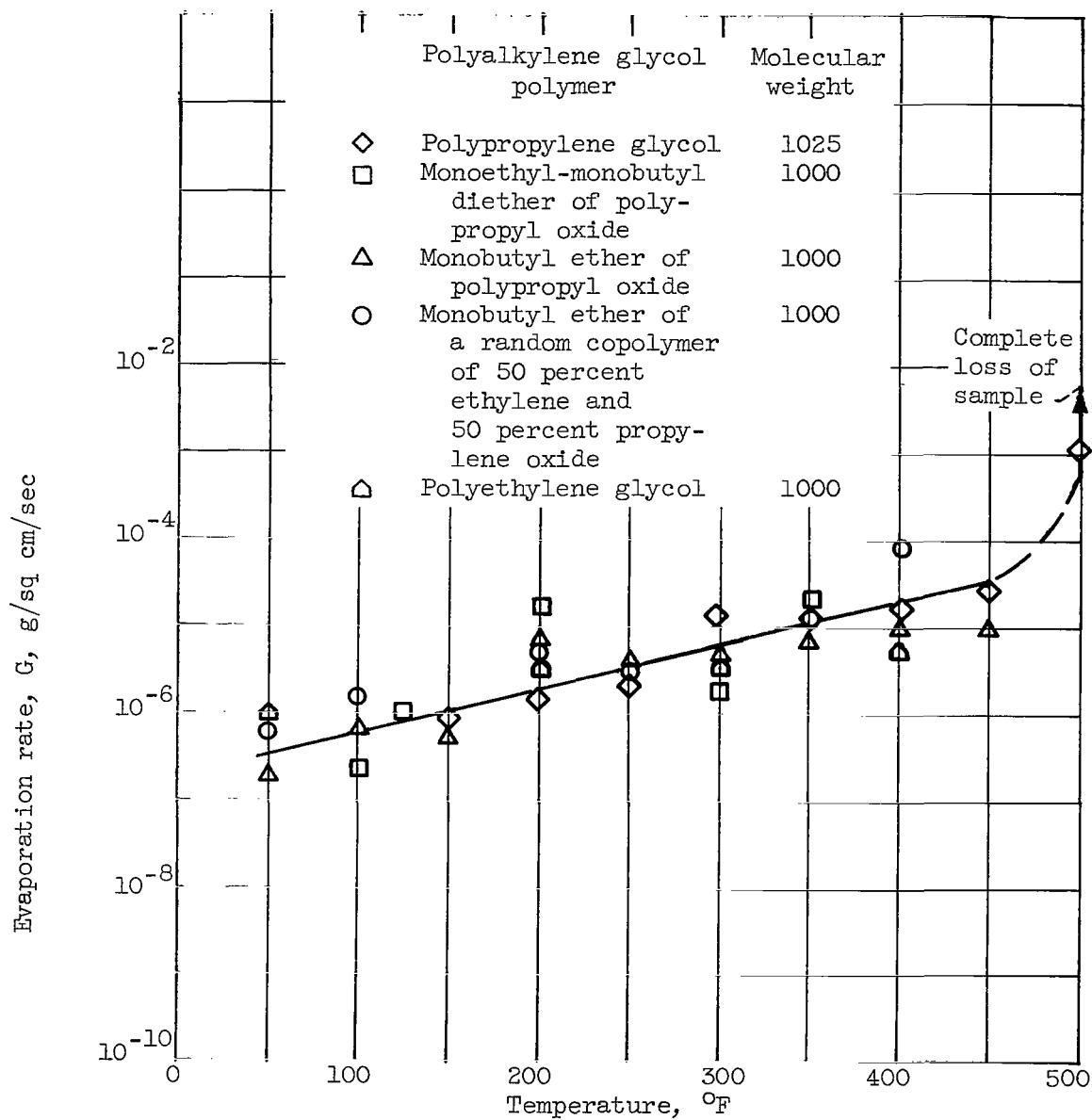


Figure 5. - Evaporation rates for various polyalkylene glycol polymers having approximate molecular weight of 1000 in vacuum ( $10^{-6}$  mm Hg).

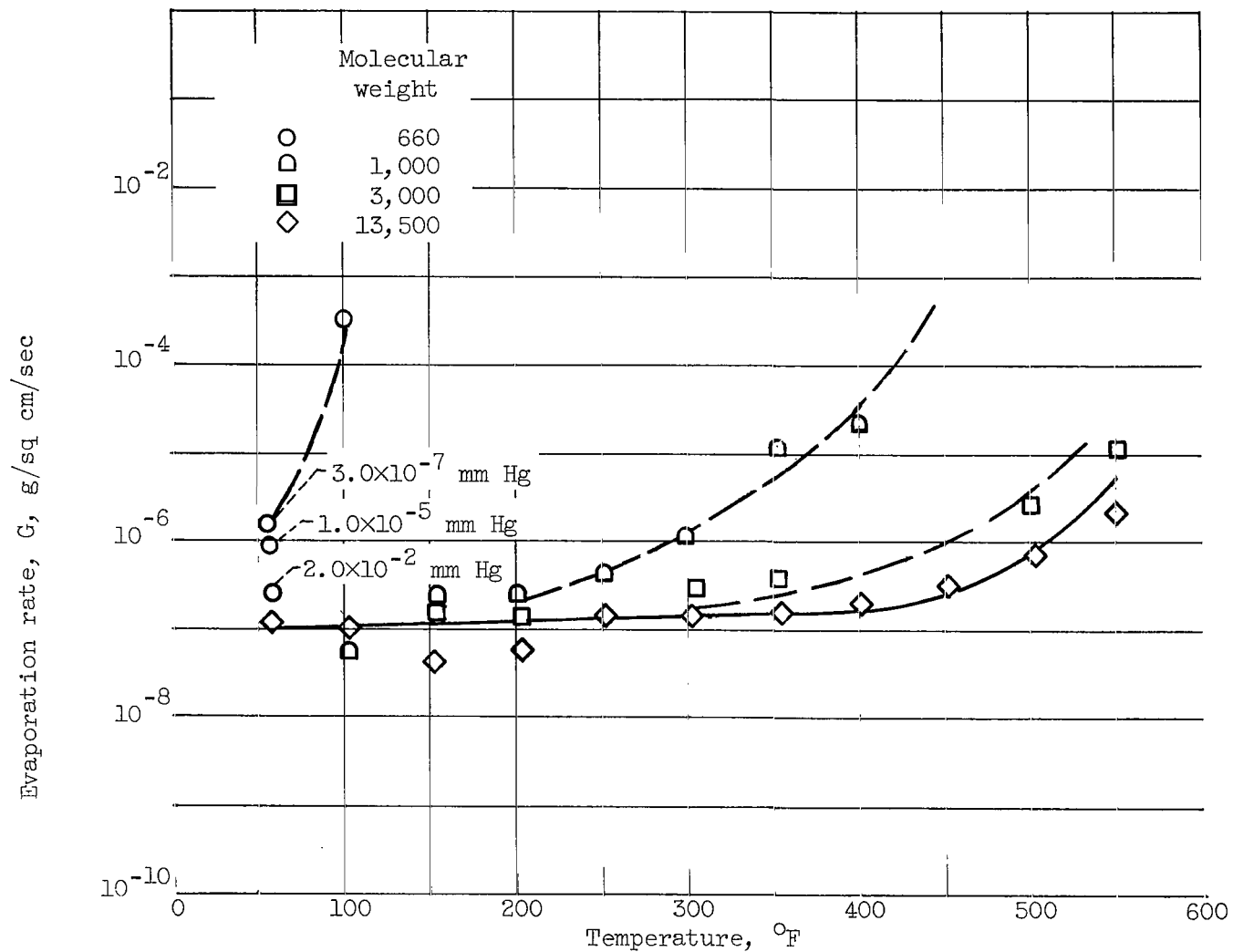


Figure 6. - Evaporation rates for various molecular weight fractions of water-soluble polyalkylene glycols in vacuum ( $10^{-7}$  mm Hg).

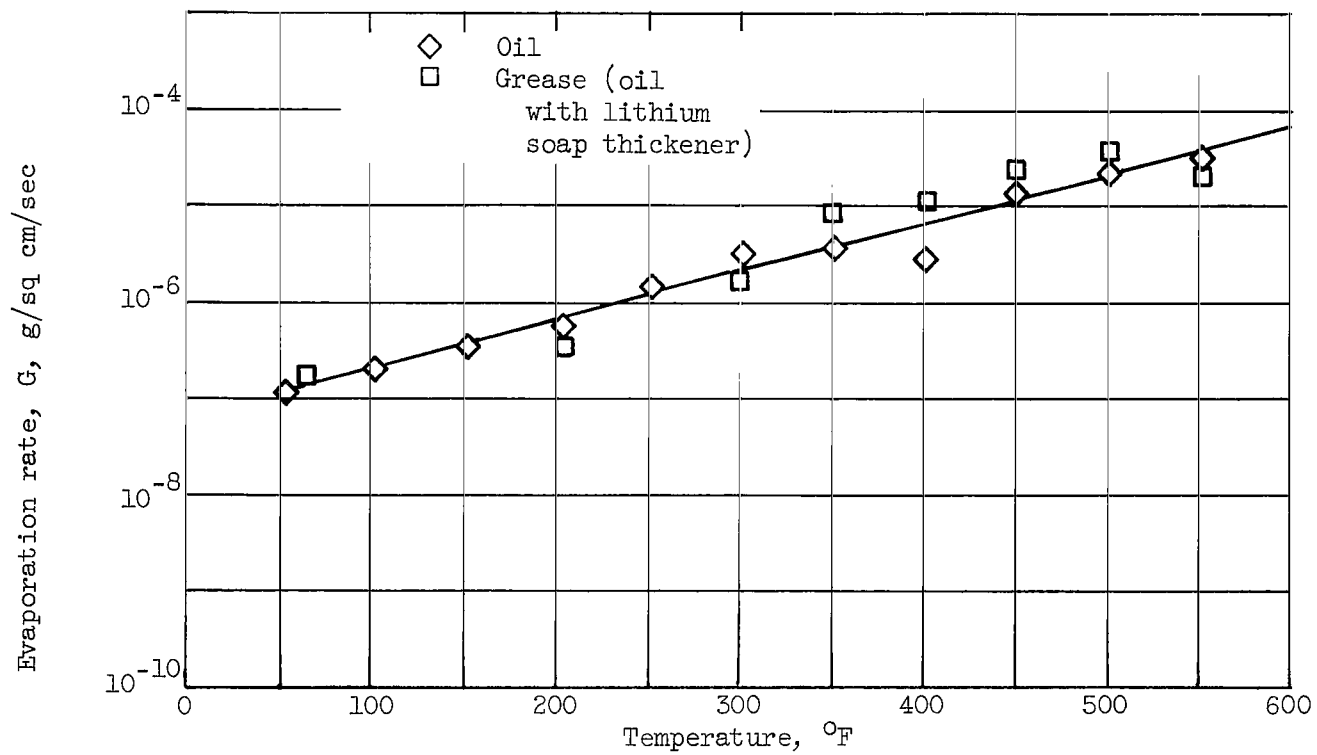


Figure 7. - Evaporation rate of methyl chlorophenyl silicone in vacuum ( $10^{-6}$  mm Hg).

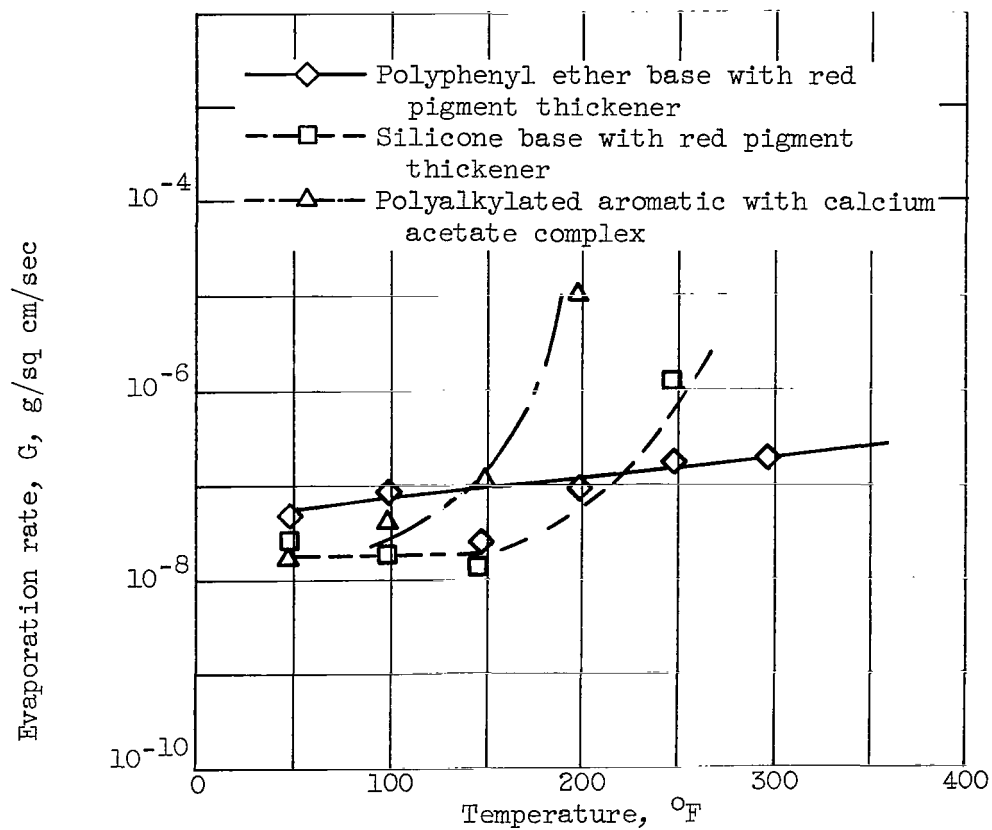


Figure 8. - Evaporation rates for various greases in vacuum ( $10^{-7}$  mm Hg).



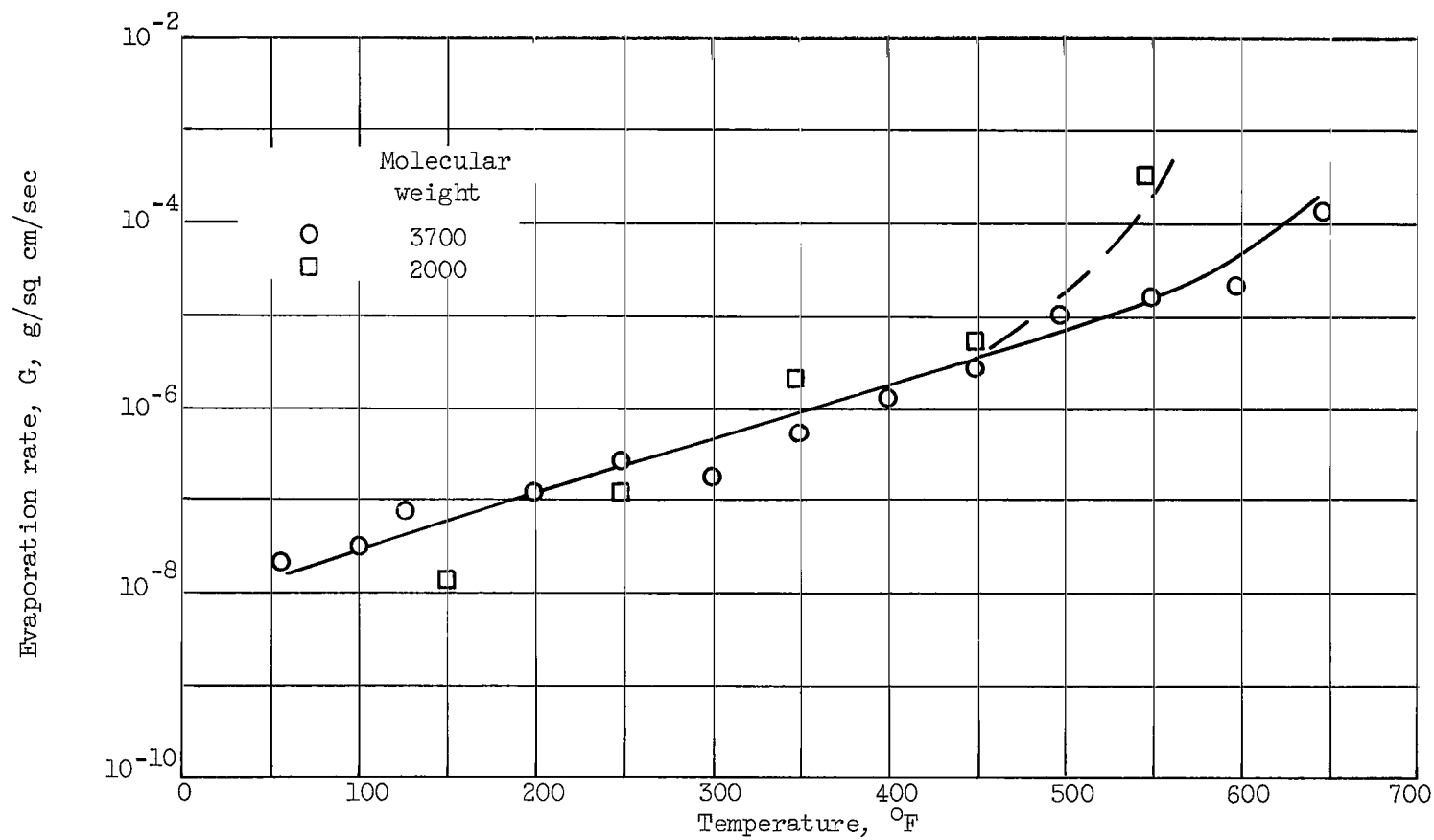


Figure 9. - Evaporation rates for two low-molecular-weight fluorocarbon polymers in vacuum ( $10^{-7}$  mm Hg).

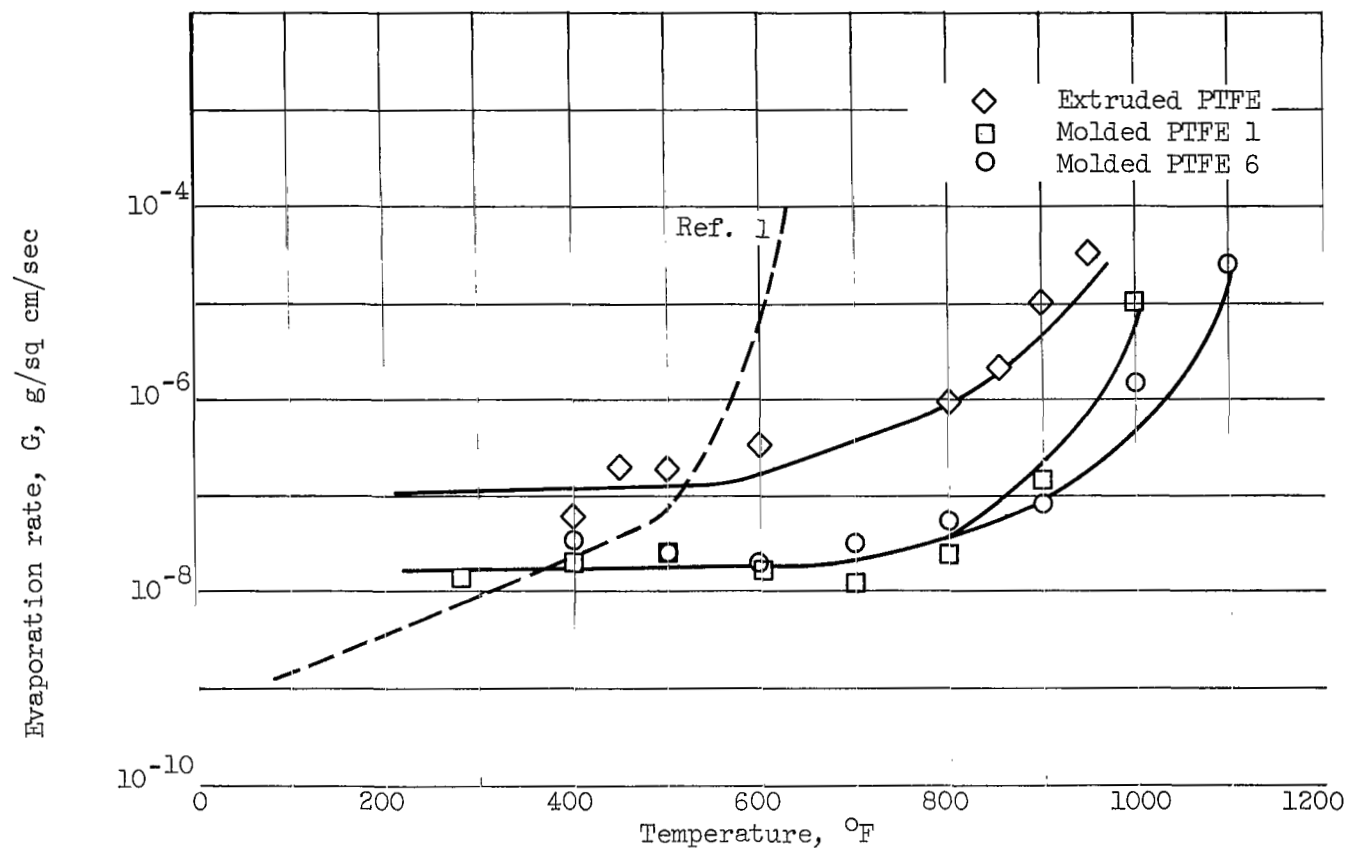


Figure 10. - Evaporation rates of various polytetrafluoroethylene compositions in vacuum ( $10^{-7}$  to  $10^{-8}$  mm Hg).

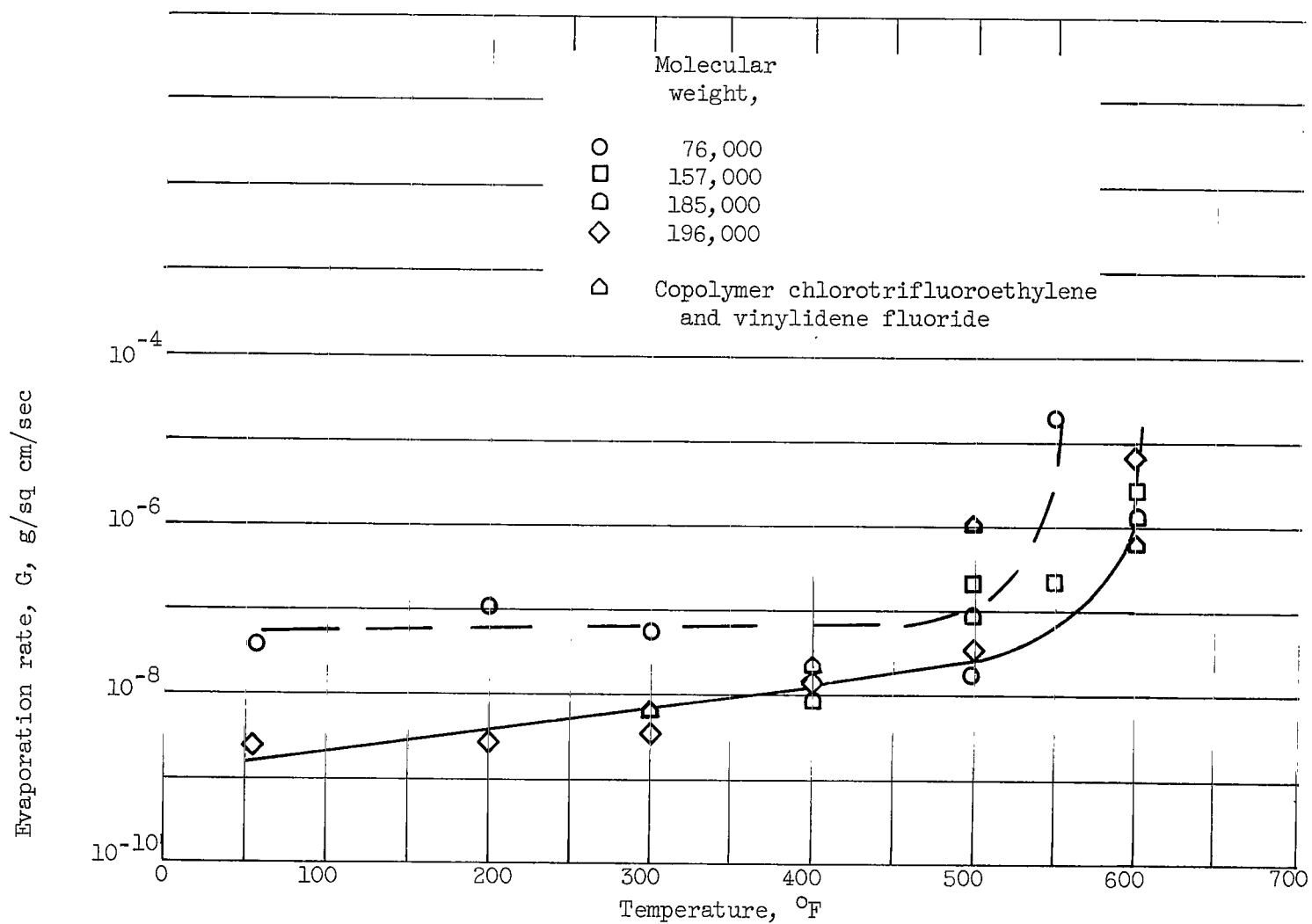


Figure 11. - Evaporation rates for various molecular weights of chlorotrifluoroethylene polymer.

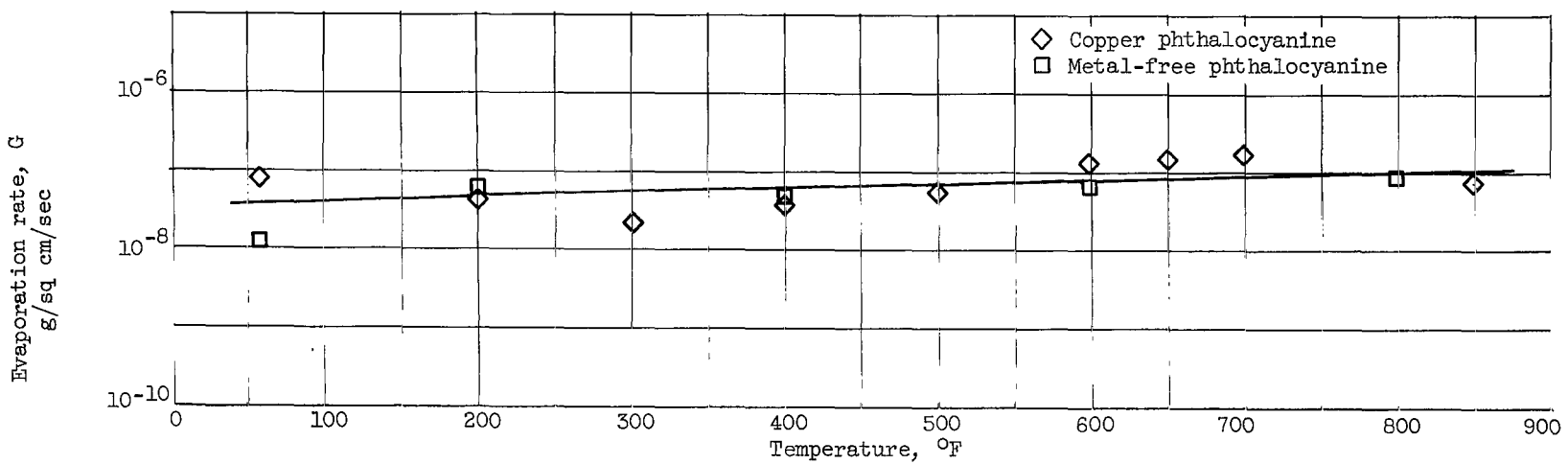


Figure 12. - Evaporation rates for metal-free and copper phthalocyanine in vacuum ( $10^{-6}$  to  $10^{-7}$  mm Hg).